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FSW of Tapered Thickness Welds using an Adjustable Pin Tool

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Why Tapered Welds?

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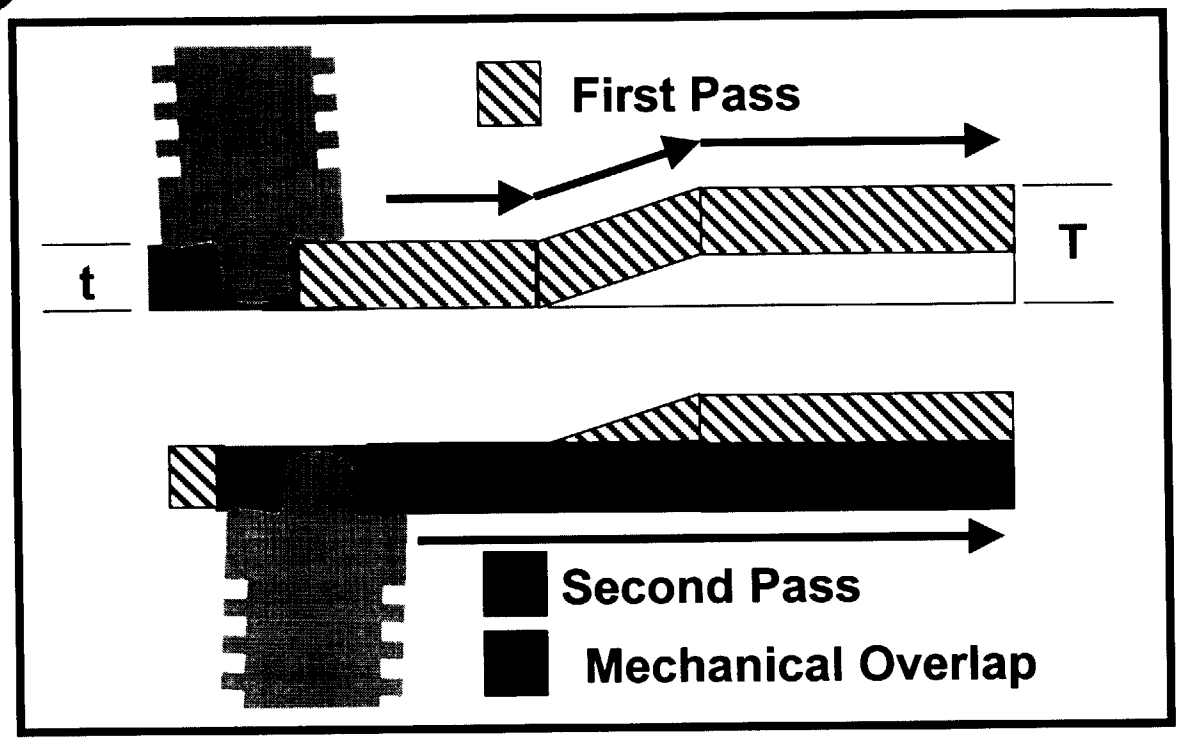
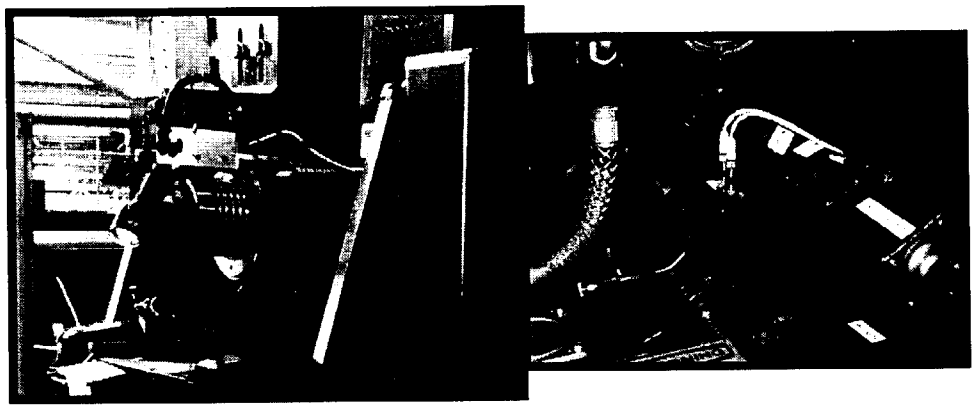
- FSW Applied to Existing Design
- Tapered Welds at Attachment Points
  - Additional thickness required for load capacity in specific regions with remaining thickness of weld land at nominal
- Tapered Welds used for weight optimization

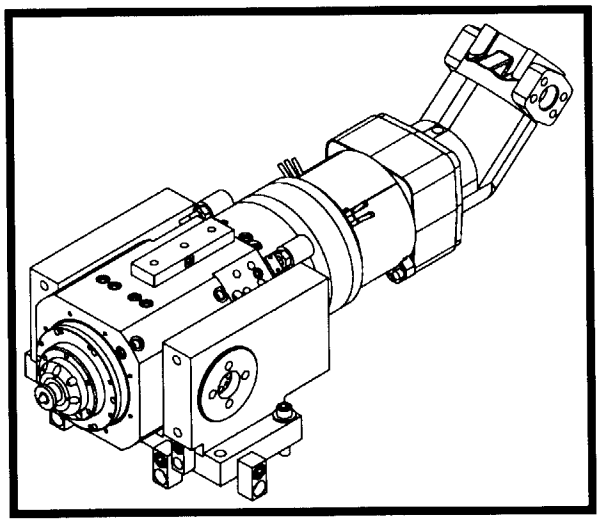
Two-Sided Approach



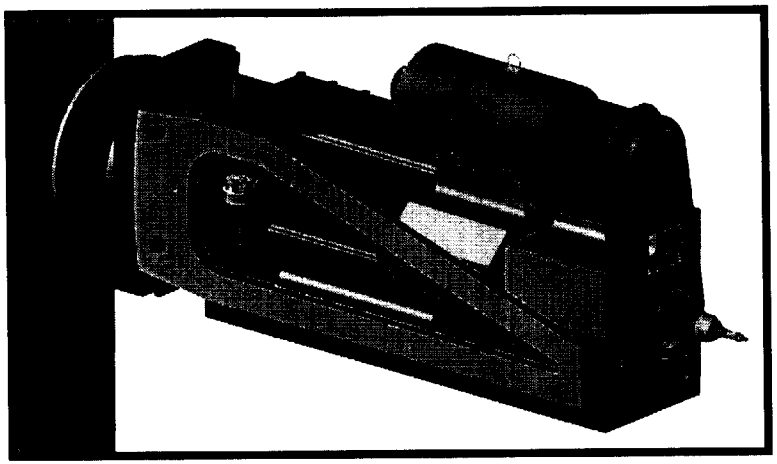
- 2 pass operation for T < 2t
- Mechanical overlap at mid thickness
  (2t-T)/T< overlap < 100%
- Potential for a mid-thickness defect that is difficult to find with current NDE processes
- Either rearrange hardware or tooling

Adjustable Pin Tools





Dependent Axes
Pin linear motion is mechanically linked to the shoulder linear motion.



Independent Axes
Pin and shoulder linear motion relative to a common base.

- **Load and/or Position Control Independently on both axes**

Adjustable Pin Tool Approach

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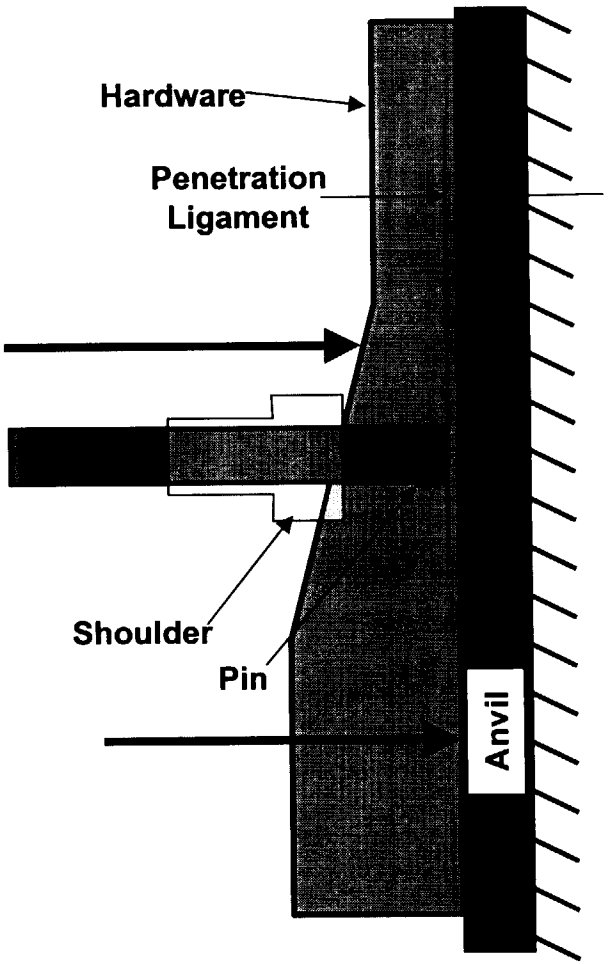
Material Surface as Reference

- Requires measurement of top surface before or during weld to determine surface profile
- Weld schedule varies pin length
- Material thickness variations affect penetration ligament
- Tooling compliance is accommodated

Anvil Surface as Reference

- Requires map of anvil surface relative to pin axis with process loads imposed to account for tooling compliance
- Weld schedule maintains pin position based on the anvil map
- Shoulder is positioned relative to top surface
- Material thickness variations do not affect penetration ligament



System Compliance

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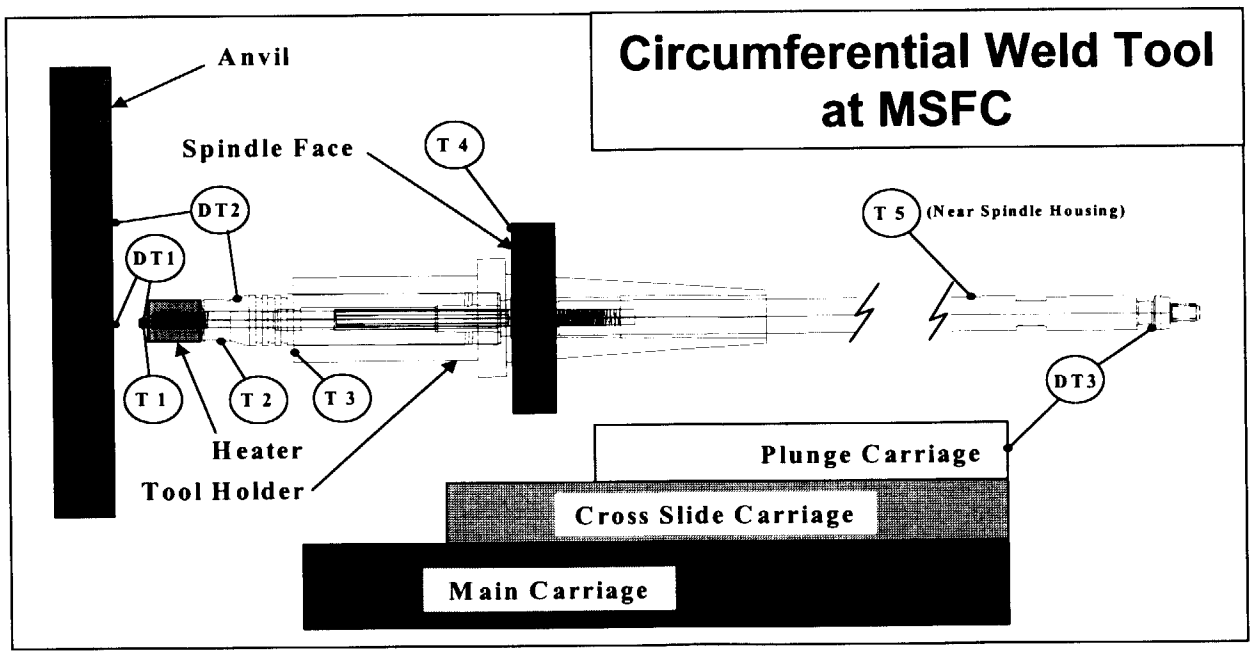
System Compliance, mechanical compression due to process loads and thermal expansion, must be quantified and compensated for during the weld process.

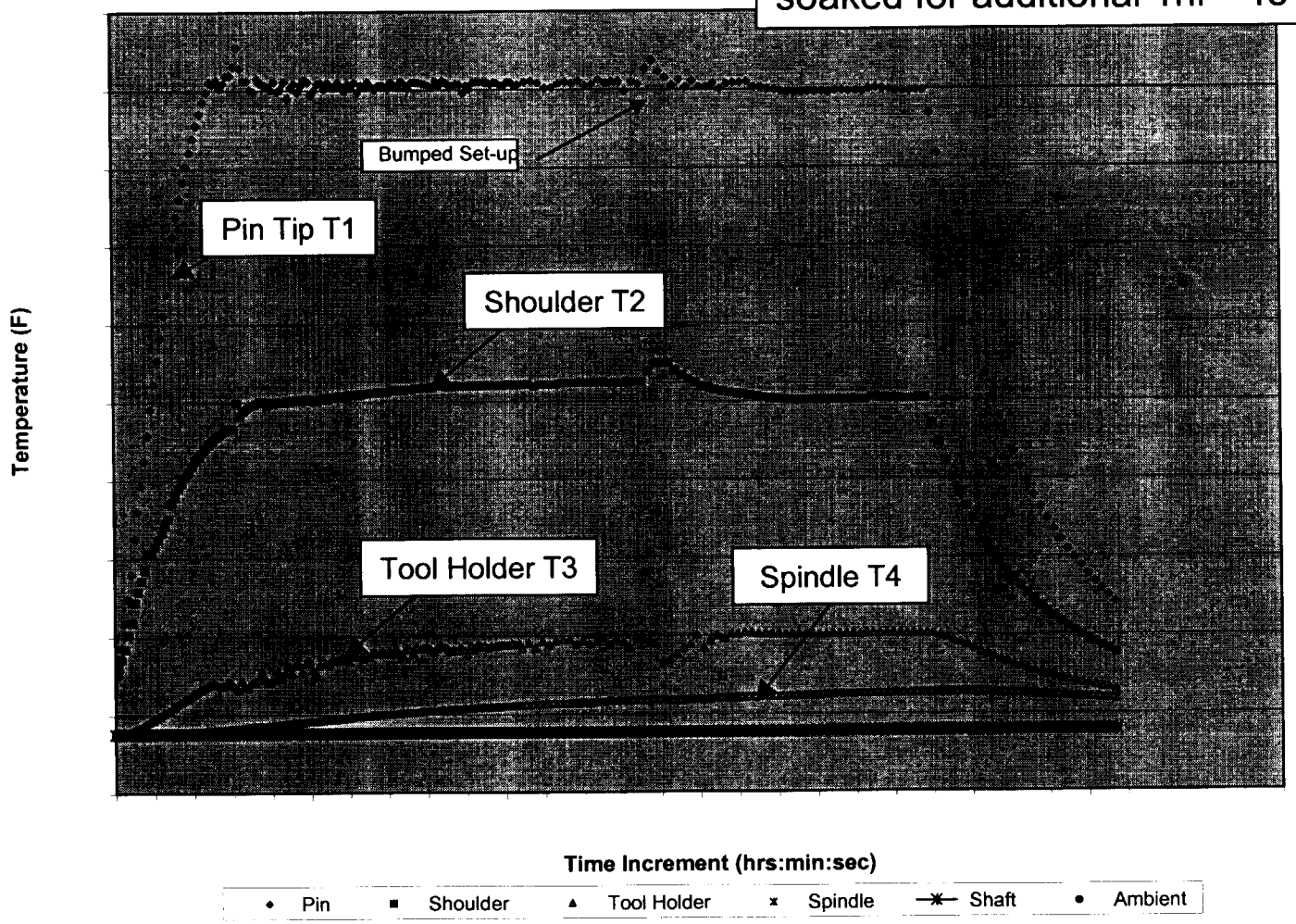
- The objective of the thermal measurements was to estimate the expansion of the pin during each weld cycle, from initiation of the weld at room temperature, through the plunge phase and into a steady state weld.
- Data was collected from measurements and analytical models.



System Compliance

Thermal Profile on Circumferential Weld Tool (CWT) at MSFC

Pin reaches process temp in 15 mins, soaked for additional 1hr - 45 mins.



System Compliance

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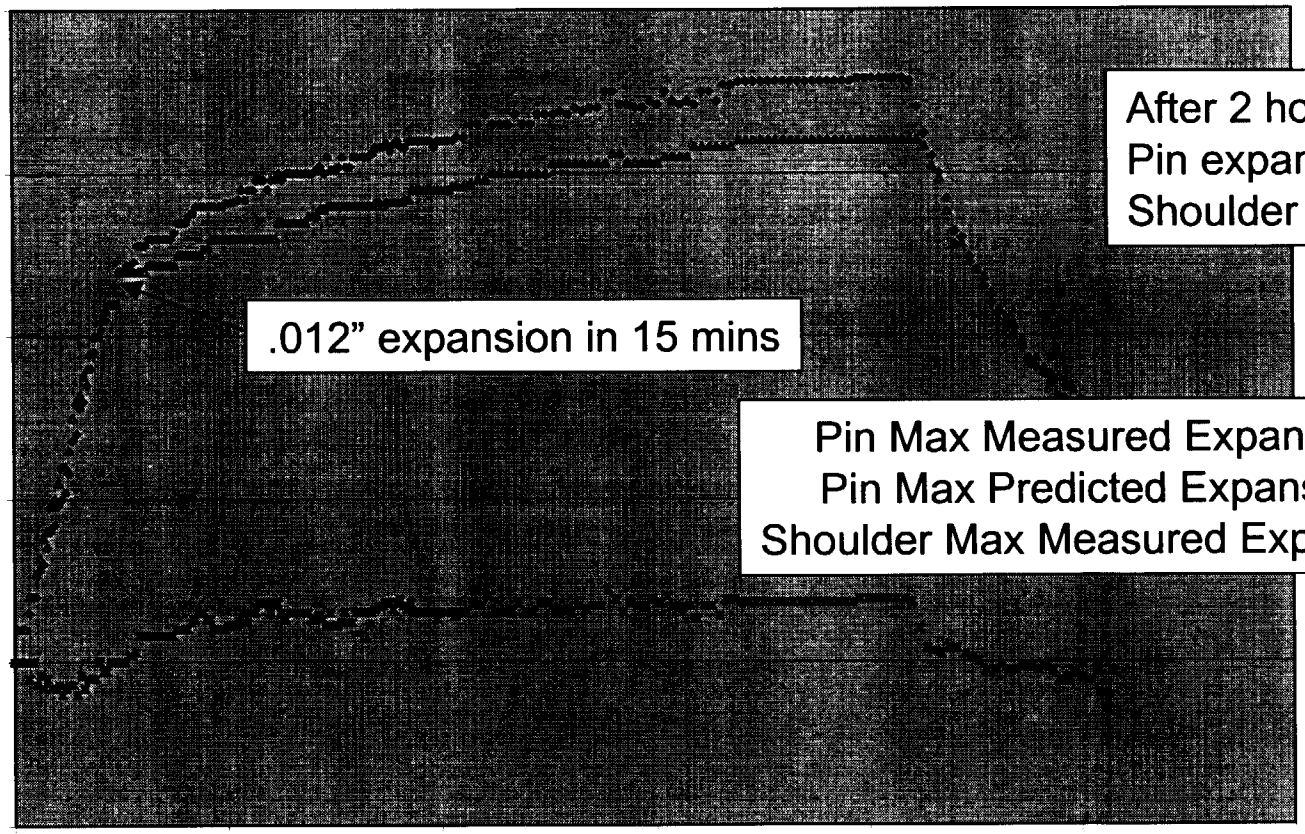
Thermal Expansion on CWT at MSFC



System Compliance

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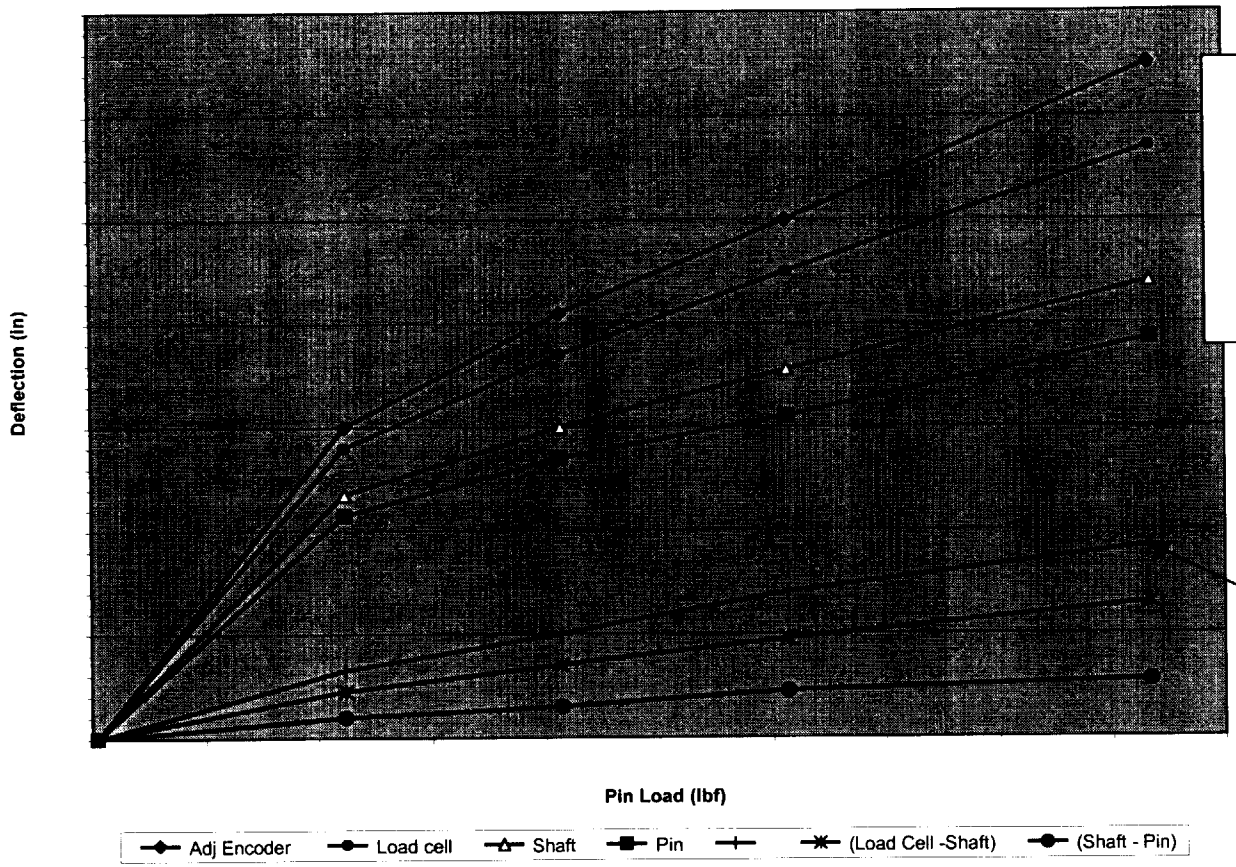
Mechanical Compliance Measurements on CWT at MSFC



Shoulder loaded to process load with no pin contact

Pin load increased from 0 incrementally to process load

Pin Compression at process load

Combined effects of thermal expansion and mechanical compliance sum to less than 0.010" compression after a 15 minute weld and ~ 0.0" after a 2 hour weld.

System Compliance

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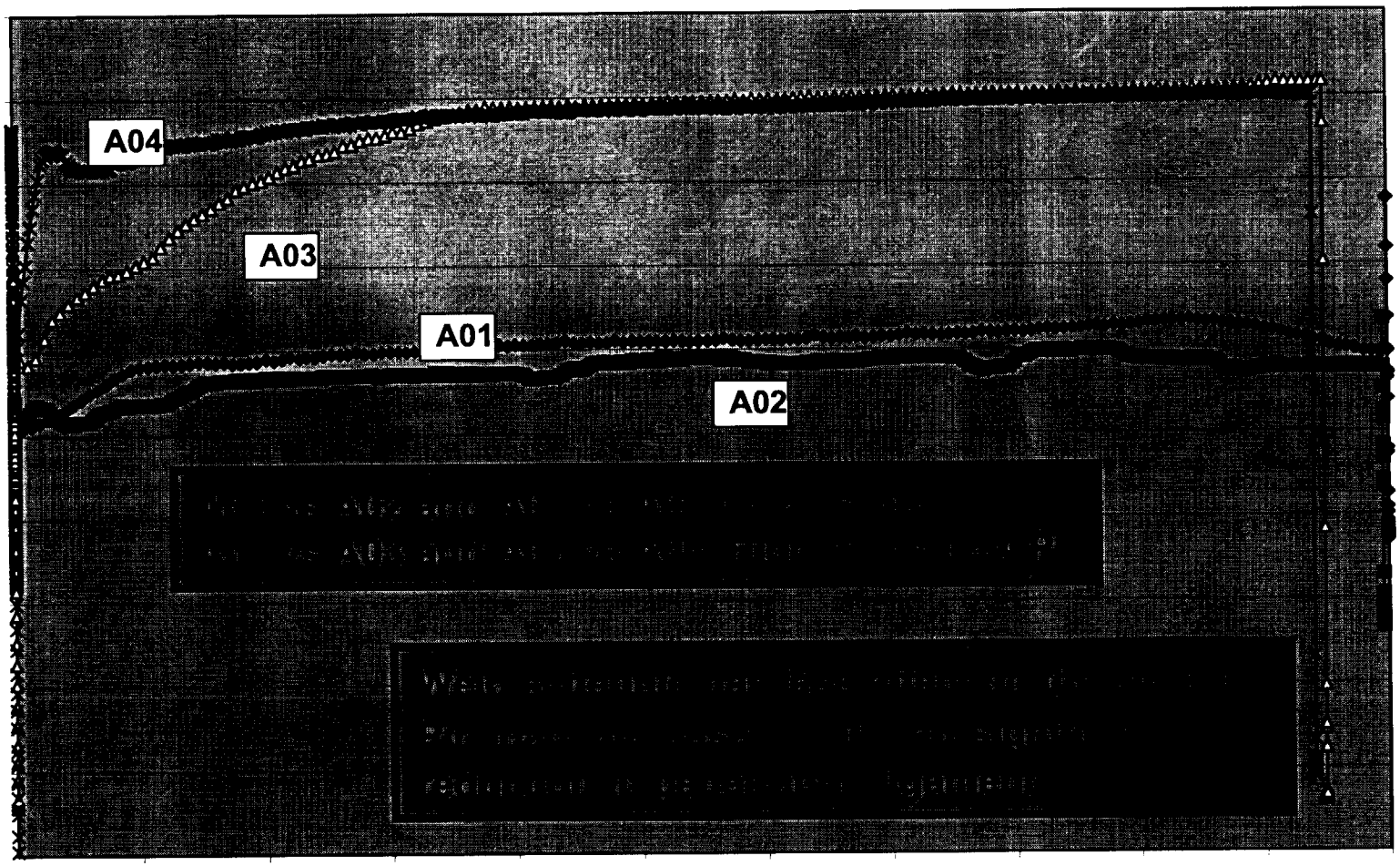
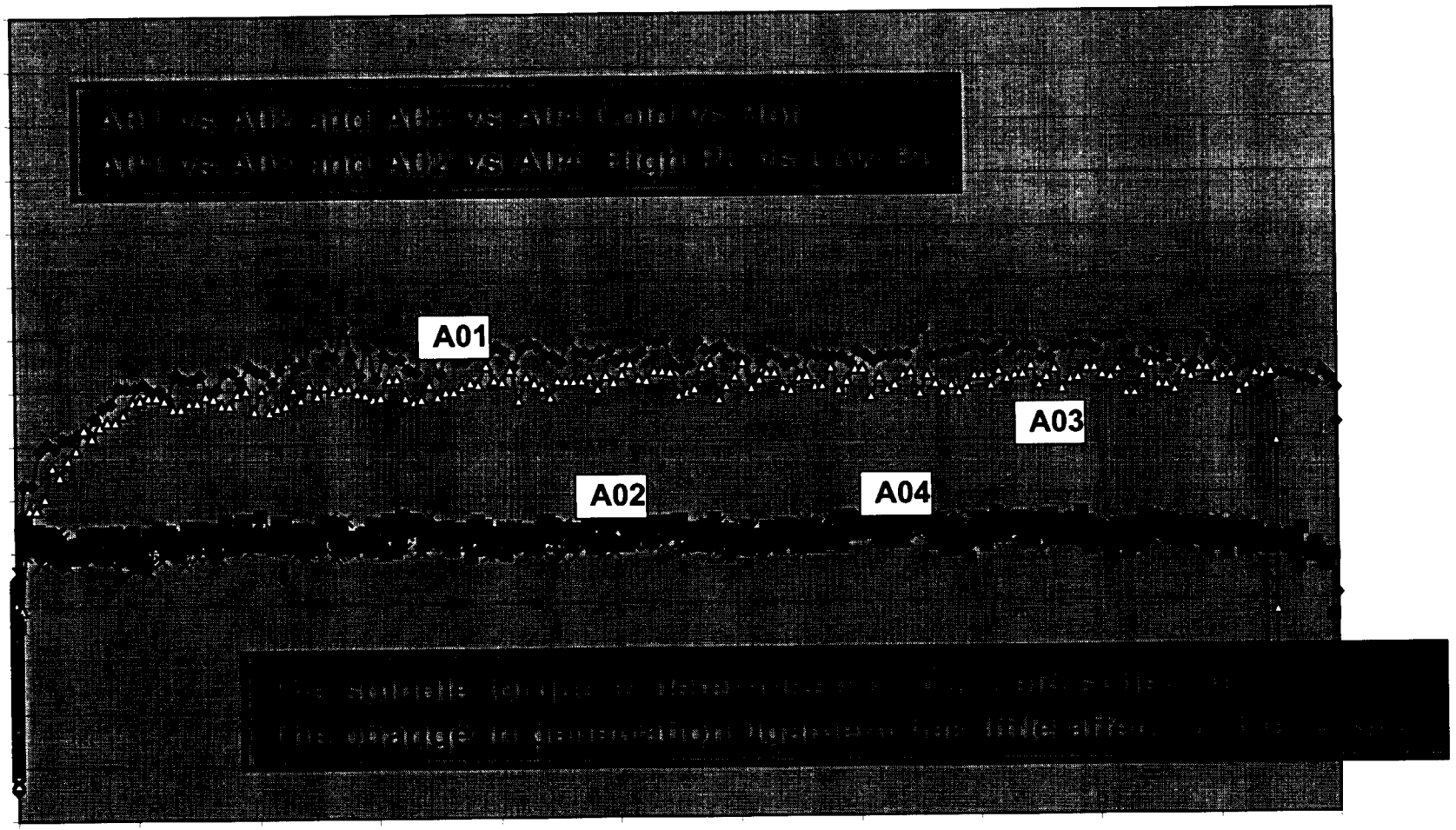
Load Measurements Objective: To qualitatively determine the effects that variations in weld parameters and penetration ligament have on pin and shoulder axial loads.

	Rotational Speed	Travel Speed	Penetration Ligament	Panel ID
Thin Plate			High	A01
			High	A02
			Low	A03
			Low	A04
Thick Plate			High	
			High	
			Low	
			Low	

Pin Load Comparison



Spindle Torque Comparison



Pin Load at Anvil Contact

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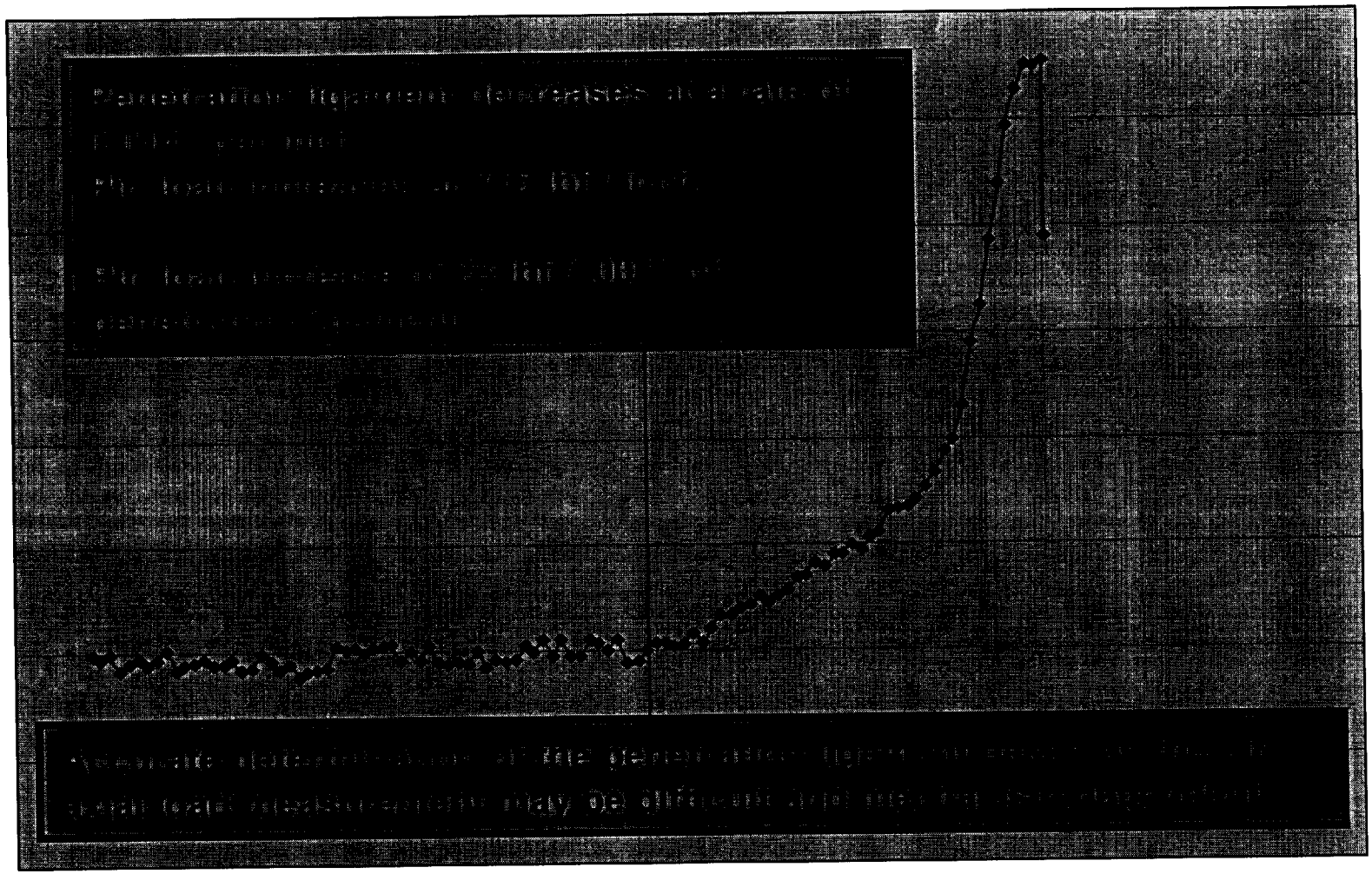

Load Measurement Conclusions

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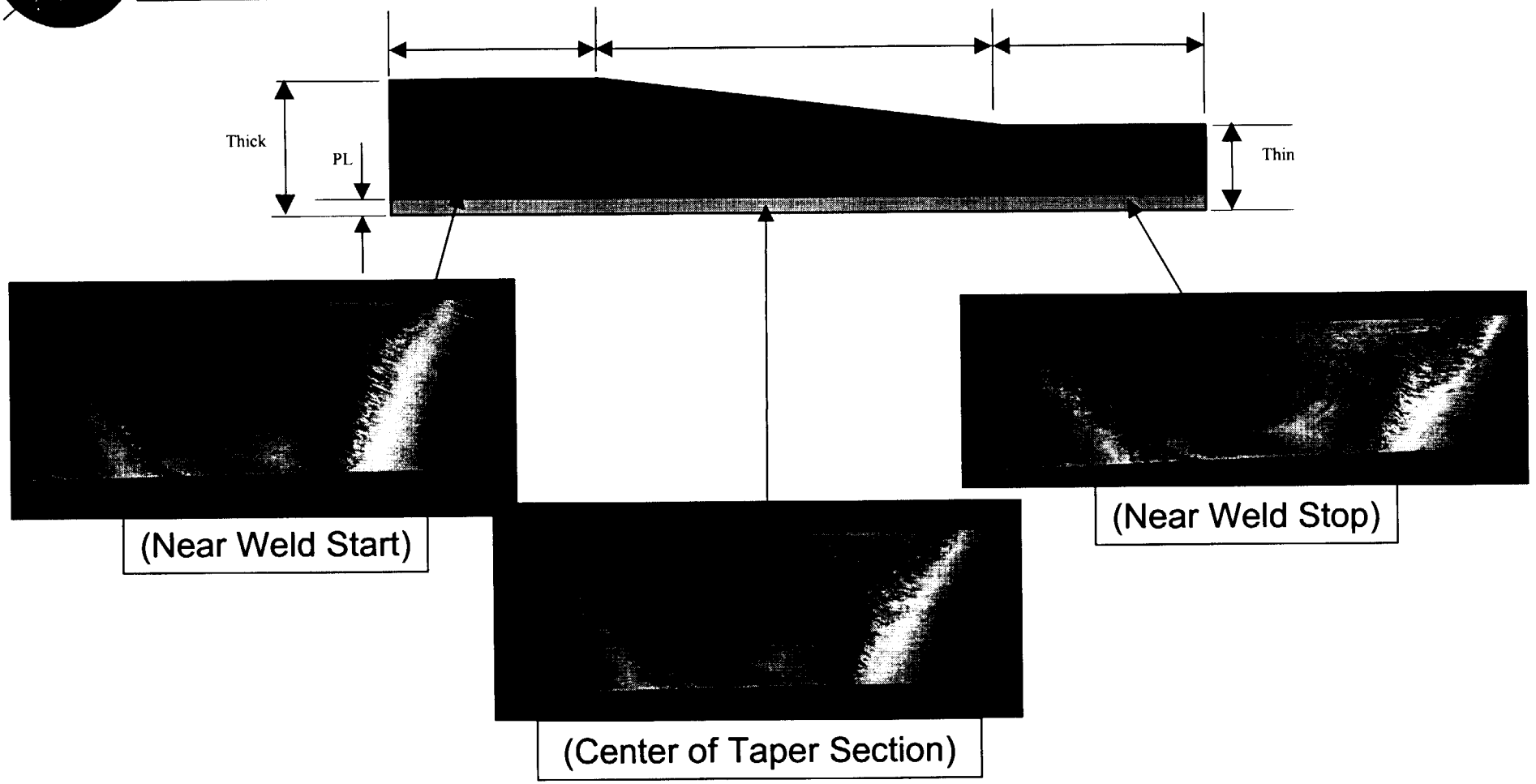
- The traverse load and spindle torque are influenced by the weld parameters (heat input). These loads appear to be unaffected by the change in penetration ligament, regardless of weld configuration.
- The penetration ligament affects the pin load significantly for the thin welds. However, this effect is difficult to discern in the thick welds.
- It is difficult to determine the effect of the penetration ligament on the total plunge load for any configuration.
- The pin load may be a good measure for post-process evaluation of weld quality and for establishing process limits, but will be difficult to use as an in-process control variable to guarantee penetration ligament.

Taper Weld Results



Mechanical compliance and thermal compensation measurements can be used to adjust the programmed pin length. Mechanical properties (UTS at RT and Cryo, YS and Elongation) in family for results from constant thickness welds.

Pin Measurement System

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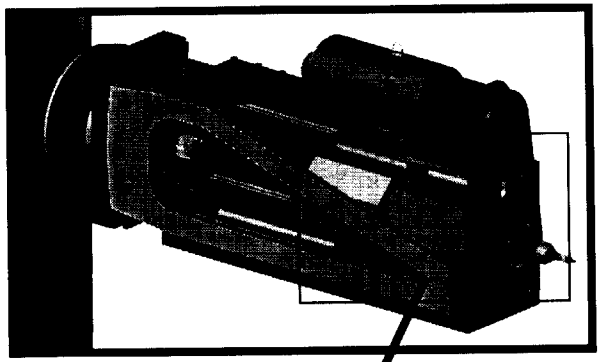
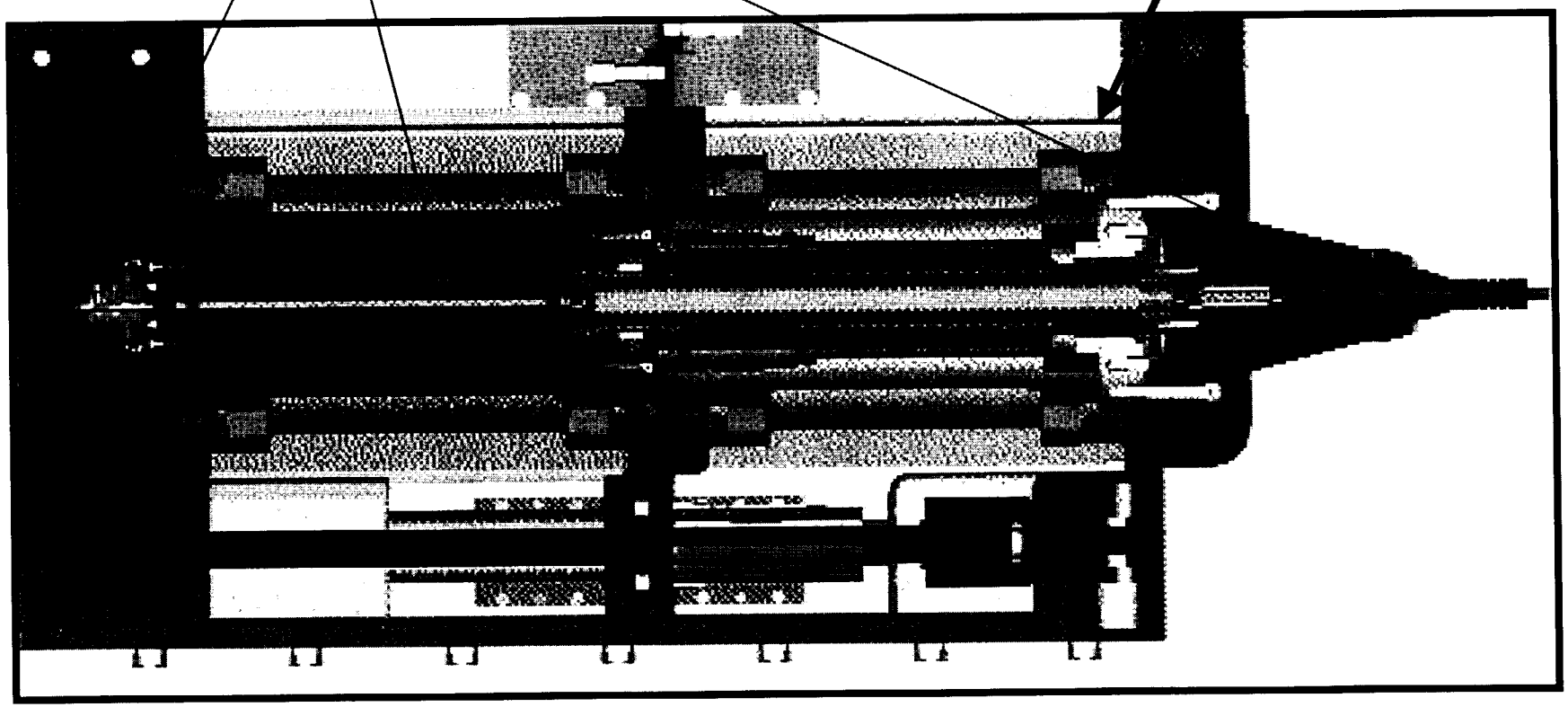
Pin Measurement System
Measurement transducer internal to spindle
Spring loaded probe not in the load path





Measurements on GTC Tool

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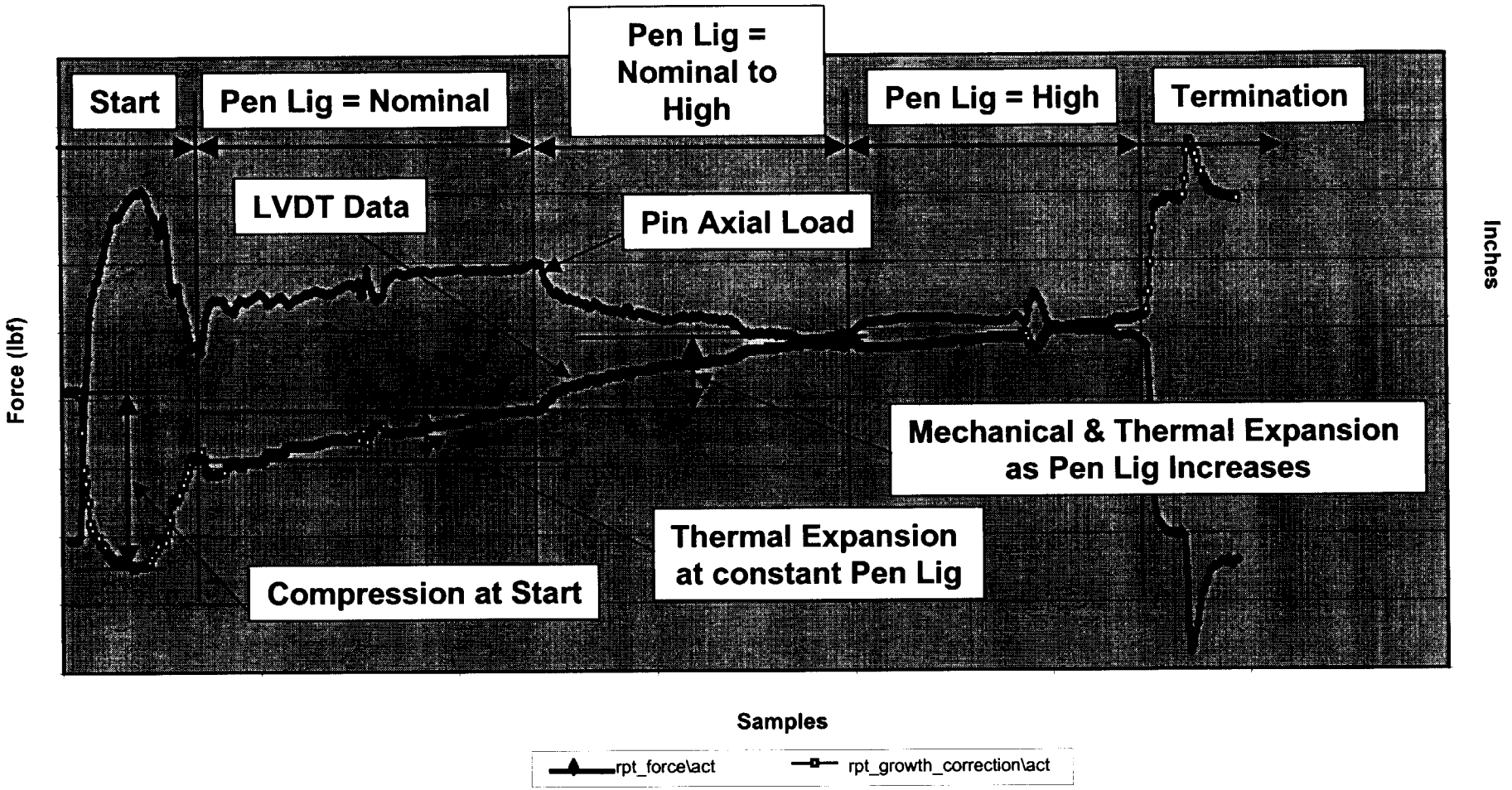

Growth Measurement System combined with compliance data provides accurate assessment of pin length changes due to mechanical compliance and thermal expansion.

Metallurgy of Varying LOP

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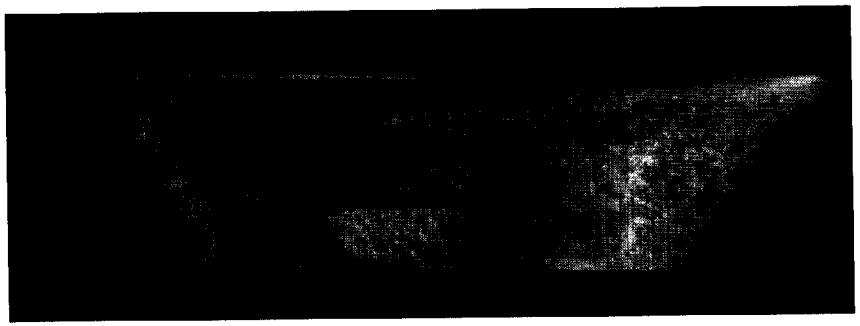
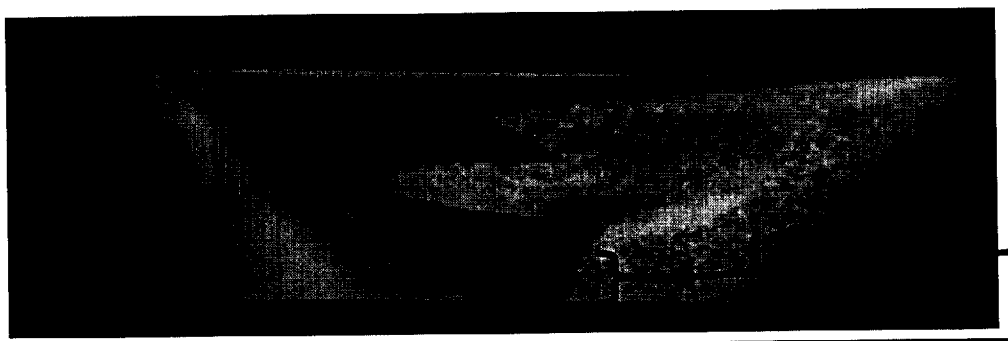
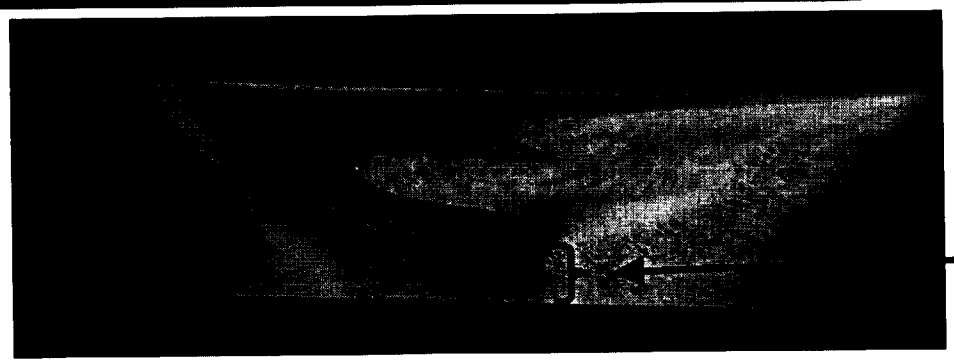
Pin Length accurately controlled to generate a continuously varying penetration ligament.



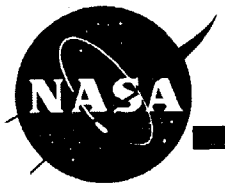
Full penetration weld at nominal penetration ligament



Partial penetration weld as penetration ligament increases (Lack of Penetration)



Partial penetration weld at maximum penetration ligament (Lack of Penetration Increases)



Process Sensitivities

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Constant thickness weld tests were conducted to investigate process sensitivities within the range of acceptable manufacturing tolerances for:

- Joint gap
- Centerline Offset
- Thickness Offset

Constant thickness weld tests demonstrated:

- Process is most sensitive to joint gap
- Centerline offset to the retreating side is more detrimental than offset toward the advancing side
- Thickness offset is most detrimental when combined with centerline offset to the side of the thinner material

Process Sensitivities

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Tapered thickness weld tests were conducted by combining each of the sensitivities at limits of the tolerances identified in the constant thickness tests.

- Joint gap ≈ 10% to 20% of material thickness
- Centerline Offset ≈ 35% of the pin radius
- Thickness Offset ≈ 4% of material thickness
- Additional offset of taper start points on either side of the weld joint did not prove significant

Process Sensitivities

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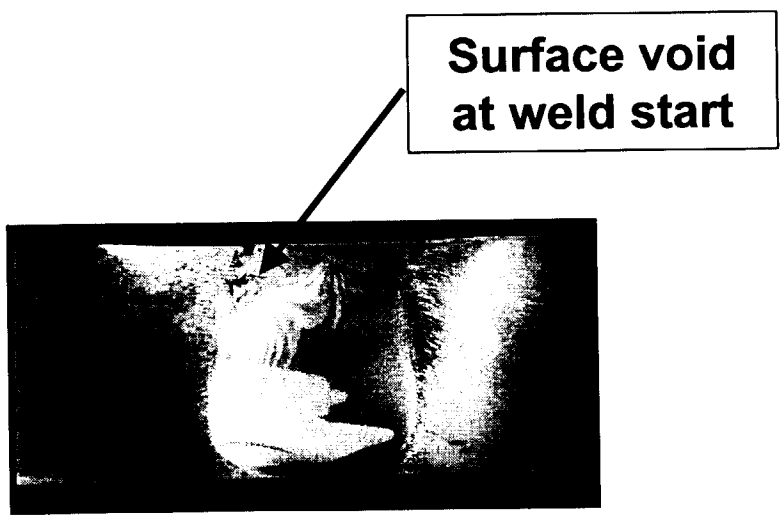
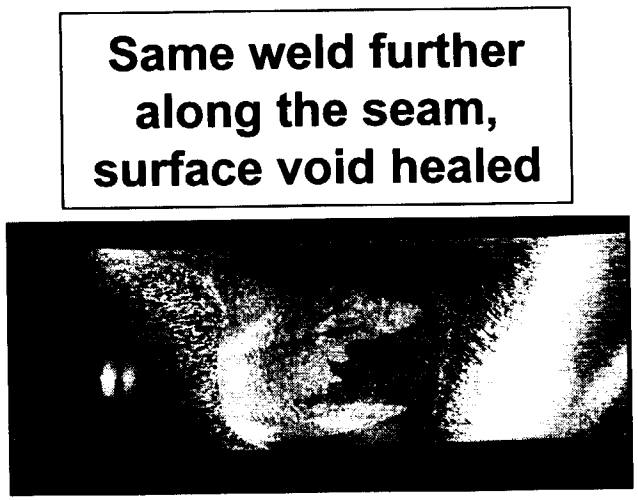
Tapered thickness weld tests demonstrated similar effects as the constant thickness welds:

- Surface measurements used to define heel plunge should be on the "thin" side of the weld joint.
- As with constant thickness welds, the joint gap had the most severe effect on the weld.
- Centerline offset to the retreating side is more likely to cause surface voids at the start of the weld.





Conclusions

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- Reliable adjustable pin tool mechanisms are available for conducting tapered FSW welds.
- Mechanical compliance and thermal expansion are competing affects that must be accounted for when conducting tapered welds with adjustable pin tool mechanisms. These data can be successfully applied to adjust pin length targets during welding.
- The use of anvil compliance maps and pin measurements systems provide an accurate method for in-situ measurements of pin position.
- Process sensitivities to manufacturing variations are essentially equivalent for both constant and tapered thickness welds.